A MARKOV DECISION MODEL OF THE MONTEREY PENINSULA WATER SYSTEM

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

A MARKOV DECISION MODEL OF THE
MONTEREY PENINSULA WATER SYSTEM

by

Charles Peter Zuhoski

September 1978

Thesis Advisor: A. Washburn

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A Markov Decision Model of the Monterey Peninsula Water System

by

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Lieutenant Commander, United States Navy
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requirements for the degree of

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I. ORIGIN OF THE PROBLEM AND THE PROPOSED MODEL

The following study was motivated by the 1975-77 California drought which prompted the controversial decision in the winter of 1977 to ration the consumption of water to the residents of the Monterey Peninsula. Individual consumption was restricted to a monthly maximum not to exceed a per capita daily consumption rate of 50 gallons. By comparison, average annual consumption figures for the normal years immediately preceeding the drought reflected a daily rate of 135-150 gallons per person.[1]

The winter of 1977-1978 brought near record rainfalls to the Monterey coast that ended both the drought and the rationing program about one year after the restrictions were placed in effect.

In retrospect, the rationing imposed represented a drastic response to the water shortage (the restriction was less than 1/3rd of normal consumption for the summer months). When the rains came in December of 1977, existing water supplies, although considerably below normal levels for that time of year, were not yet considered to be near the point of exhaustion. These facts considered, a number of questions

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[1]Unless referenced otherwise, all statistics concerning the Monterey Peninsula Water Supply and consumption were obtained from the California American Water Company.

arose concerning the decisions made. First, could the rationing have been made less drastic by enacting milder restrictions? In view of the eventual return to above normal rainfall conditions, was the decision made too hastily? Finally, if the answer to either of the preceeding questions is yes, then does there exist some procedure that the decision-maker can use that will provide him with a realistic rationing policy for water consumption that is both timely and optimal with respect to some reasonable criterion.

An answer to the last question is the subject of this study. The model presented, although designed specifically to accomodate the Monterey Peninsula situation, can and has been generalized to fit many other water resource allocation schemes, particularly in the area of flood control and/or multiple use water resource systems.

The approach to the problem was suggested by Dr. Alan Washburn at NPS, Monterey. The stochastic nature of rainfall, the sole replenishment source of water for the peninsula, suggests some form of a Markov decision process since subsequent supplies of water are affected by both deterministic (consumption) and random (rainfall) processes.

Utility of water to the population was selected as the measure of benefit to be used in the objective function because of the life style of the Peninsula.[2] Approximately

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[2]The term "Monterey Peninsula" shall be used to represent an area known to the California State Department of Water Resources as Zone 11 and includes Carmel Valley, Carmel, Monterey and parts of Seaside.

86% of the water metered to the peninsula is used to meet residential and other human uses. Less than 1.3% is used in local industry. For this reason it is difficult to attach economic values to water that other models of this type have done. Whether the actual utility of water for the population can be measured is a question that will be discussed later in detail.

Assuming that such a utility function, U(D), can be determined for the population where D = water available for consumption, then a natural objective of the decision-maker is to establish a consumption policy that will maximize the total utility of consumption.

The nature of the hydrological cycle of the Carmel Valley watershed[3] relies on yearly rainfall to provide the runoff necessary to replenish water supplies depleted by consumption and other losses. Therefore, the supplies available for future consumption are dependent upon both current consumption and future runoff. The current or near-future consumption is determined by policy while future runoff is dependent on rainfall which is random.

It is reasonable to assume that the population derives utility from future as well as present consumption. It is equally reasonable to assume that the utility of future

---

[3]The 255 square miles of the upper and lower Carmel Valley constitutes the major source of rainfall runoff used to recharge the Monterey Peninsula water supply.

consumption is not as important as that of present or near future consumption. For this reason, the concept of present value of the utility of future supplies is useful and the model in fact employs just such a concept in its objective function.

The objective then is to select a policy for current or near future consumption that will maximize the total utility associated with that consumption plus the present value of the utility of all future consumption, the supply for which is not yet known by the policy maker. What is known once consumption policy is set is the amount of water lost from storage. Now, if rainfall could be predicted and its effect on water supplies known, the objective function would be complete. However, for this model, future rainfall cannot be predicted. What can be estimated is the probability distribution of annual rainfall which can then be used to compute expected utility of future consumption.

The final objective of the model, therefore, is to choose a consumption decision from among all possible decisions available that will maximize the sum of the utility of that decision plus the present value of the expected value of the utility of future consumption.

The decision period selected is one year in length. Since timeliness of the decision is a factor, the date selected for the model's decision is the first of May. This is a particularly meaningful date since it represents not only the end of

annual rainfall for seven months but also the beginning of the period of heaviest daily consumption of water.

Graphically the model can be represented as a series of stages (see figure 1), one for each year into the future. Entering the n^{th} stage are the state, X_n, representing the amount of water stored in the supply system, a decision D_n representing allowable consumption and an amount of runoff, R_n. Leaving the stage is the new state X_{n-1} that will enter the (n-1)th stage. Finally, associated with each stage is a value $U(D_n)$ that represents the utility associated with D_n.

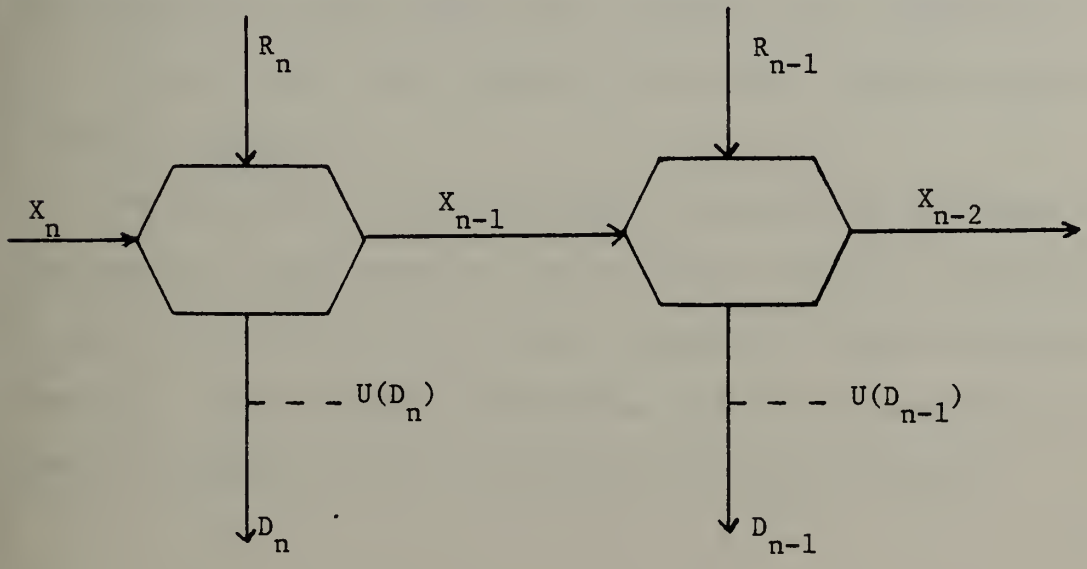

Figure 1

The concept of the model is now complete.[4] The following are required for the model to work:

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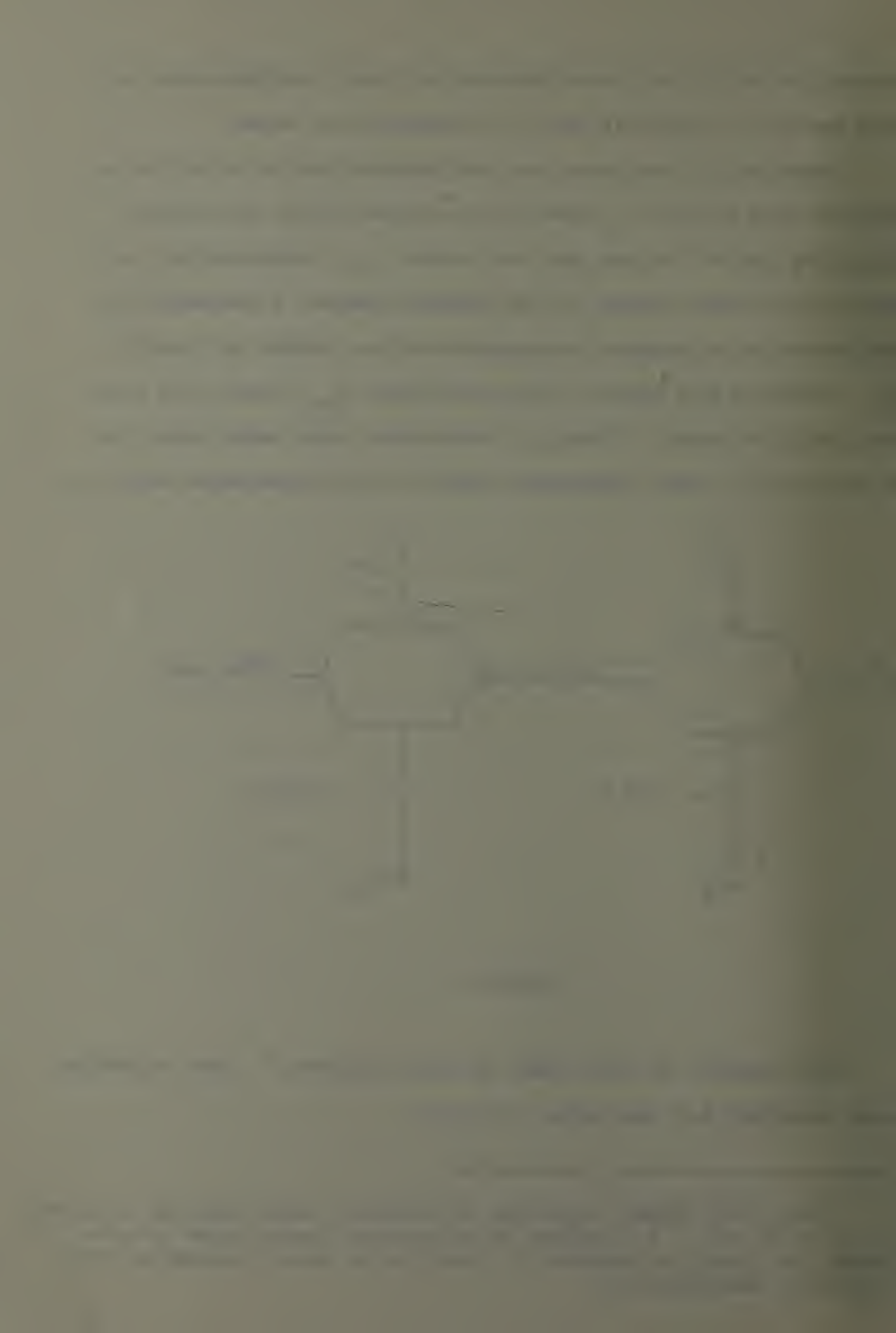
[4]The final model required is somewhat more complex as shown in Section III. A complete mathematical description of the model is given in Appendix A, containing final parameter and function descriptions.



1. The utility function U(D) which associates an arbitrary value U(D) with the consumption quantity of water, D.

2. The replenishment function that will estimate, for a given rainfall, the amount of water available for return to the water supply.

3. The maximum total storage capacity of the system.

4. The probability distribution for rainfall.

Each of these sub-models is developed in one of the remaining sections of this study followed by a discussion of the results of the model under various assumptions. The study concludes with some additional remarks and recommendations for future study that resulted from the research associated with this study.

The majority of hydrological information and data was provided by the Monterey County Flood Control and Water Conservation District and the California American Water Company. Their eager assistance and full cooperation have been invaluable in the completion of this project.

II. RAINFALL – THE SOLE SOURCE OF WATER

The most extensive rainfall records have been maintained at the Forest Lake holding reservoir near the coast. Records there have been kept since 1896 with only a few missing values. Additional rainfall data was examined at three other sites; Pacific Grove, Los Padres Reservoir and San Clemente Reservoir. The Pacific Grove and Los Padres records have been kept since the mid 1940's while San Clemente records reach back to 1921.

The rainfall in the upper Carmel Valley appears to be about 5 inches more annually than on the coast. This fact is consistent with the climatological conditions of the central California coast. Of the four sites, the Los Padres dam rainfall data seems to have the highest correlation to the runoff data computed in Section III.

Reference 1 presents some analytical procedures for accurately modelling the total precipitation volume for a watershed using the rainfall data from several gauge sites. One method employs polygonal areas of constant precipitation. Another uses contour lines of equal precipitation. All of them, however, seem to rely on a reasonably dense distribution of rain gauge data across the watershed. Such data is not presently available for the Carmel Valley.

The data that is available suggests that use of single site rainfall data could provide an adequate indicator of

total precipitation over the entire watershed. The simple correlations between the four sites examined indicate a strong dependence. The small areal extent as well as the local climate seem to preclude independent rainfall behavior within the watershed.

Since Los Padres rainfall provided the best model of runoff, it was selected as the annual rainfall to be used in computation of expected utilities. Successive annual rainfall measurements at Los Padres were assumed to be independent random variables. Serial correlation of existing data was low and its possible effects were ignored.

A cumulative probability distribution (CDF) of annual rainfall was then constructed from the existing 30 data points and is shown in Figure 2. The CDF can now be used to graphically extract the probability mass function required by the model. Table I contains the probability mass function used by the final model.

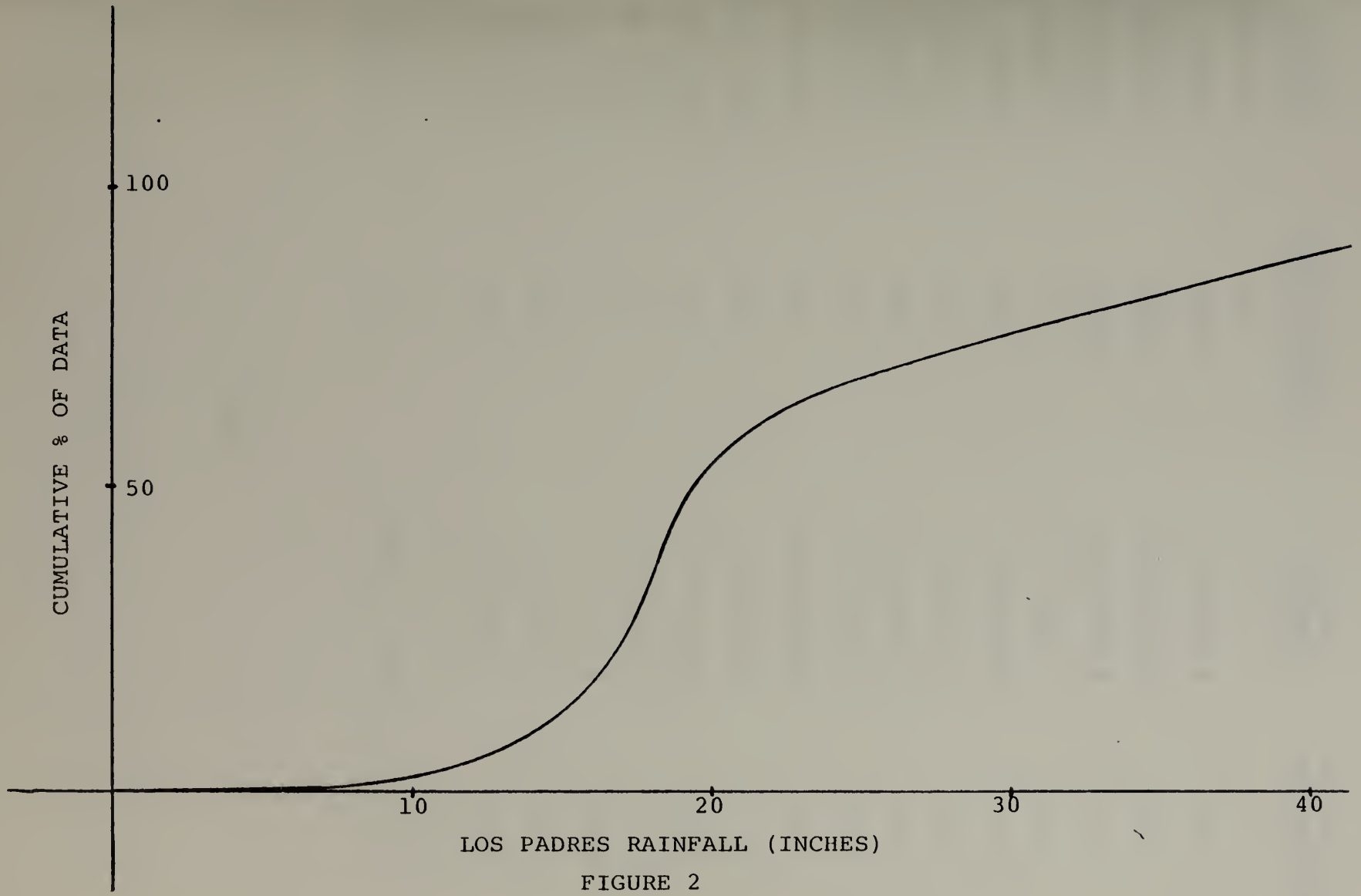
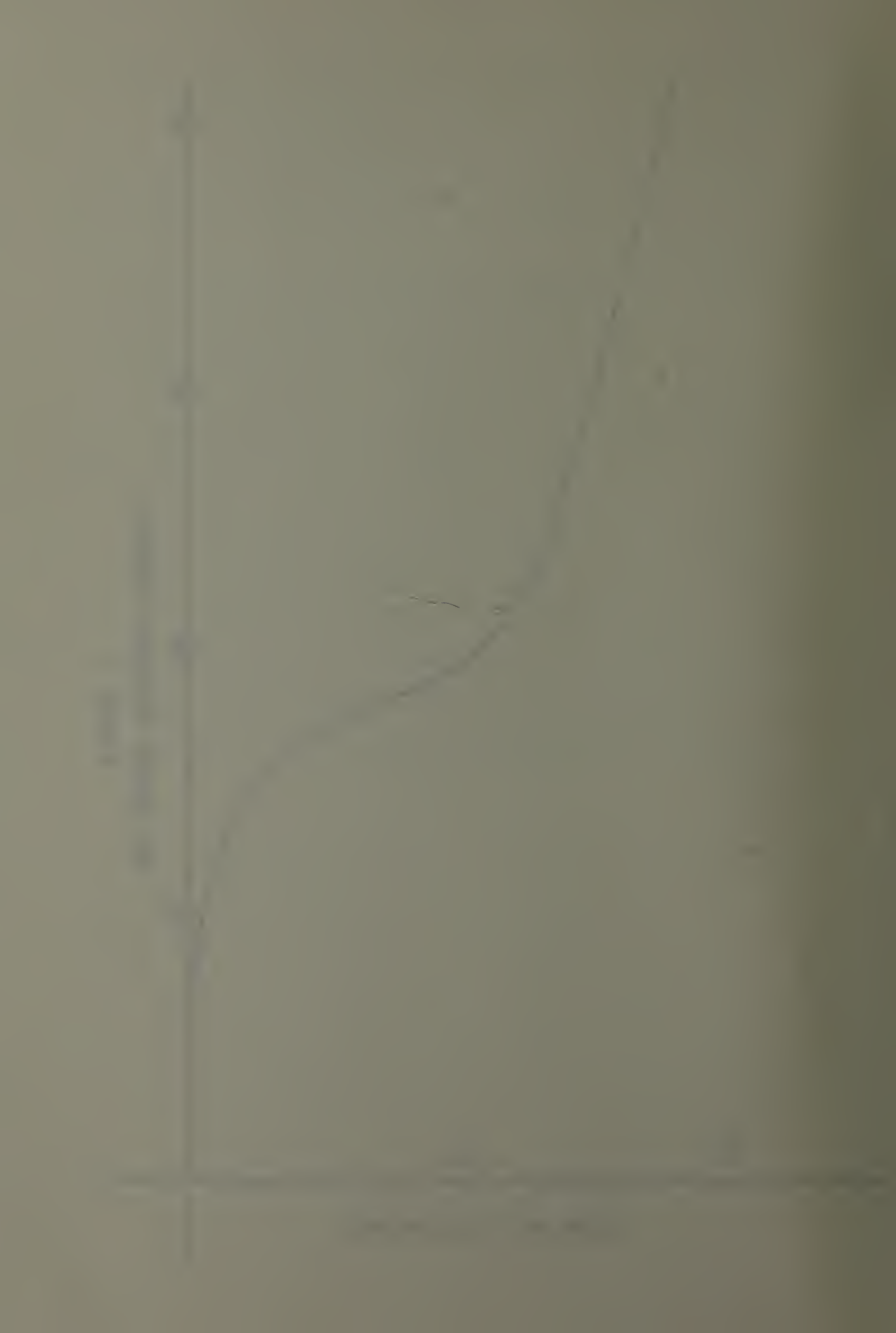

100
50
CUMULATIVE % OF DATA
10
20
30
40
LOS PADRES RAINFALL (INCHES)

FIGURE 2



Rainfall (inches)	Probability of Occurrence	Rainfall (inches)	Probability of Occurrence
Less than 1.5	.002	18.5-19.5	.12
1.5-2.5	.0005	19.5-20.5	.06
2.5-3.5	.0005	20.5-21.5	.04
3.5-4.5	.0005	21.5-22.5	.035
4.5-5.5	.005	22.5-23.5	.025
5.5-6.5	.006	23.5-24.5	.02
6.5-7.5	.006	24.5-25.5	.02
7.5-8.5	.006	25.5-26.5	.015
8.5-9.5	.009	26.5-27.5	.015
9.5-10.5	.011	27.5-28.5	.015
10.5-11.5	.011	28.5-29.5	.015
11.5-12.5	.015	29.5-30.5	.015
12.5-13.5	.016	30.5-31.5	.013
13.5-14.5	.024	31.5-32.5	.012
14.5-15.5	.035	32.5-33.5	.011
15.5-16.5	.047	33.5-34.5	.010
16.5-17.5	.078	34.5-35.5	.010
17.5-18.5	.102	Greater than 35.5	.1745

Table I

III. THE MONTEREY PENINSULA WATERSHED — A STUDY IN HYDROLOGY

A major effort of this study involved the question of replenishment of water supplies to the storage system given the current years rainfall. This is actually a generalization of several more specific questions.

How much storage is available for collecting the water generated by rainfall? How much is lost to the system and how? Does runoff due to rainfall depend only upon current rainfall or are there other factors to consider? The answers to these questions provide a model of the watershed that is sufficient to complete the general model.

A. TOTAL CAPACITY OF THE SYSTEM

Recent studies [Ref. 2,3,4,5] have been made of the Carmel Valley watershed, the major source of surface and ground supplies of usable water for the peninsula.[5] One of these studies was conducted in 1974 by the California Department of Water Resources with a revision to the study submitted in December 1977. Its purpose was to "conduct an independent study of the yield of the ground water basins in the service area ..." (of Zone 11) [Ref. 2]. Zone 11 comprises the entire

---

[5] There are wells in the Seaside area that provide limited supplies but are not considered part of the Carmel Valley watershed. Their input to the system is small and will be treated as constant.

Carmel Valley, Monterey Peninsula and Seaside area. The study addressed surface storage and two principal aquifers, the Carmel River Valley alluvium and the Seaside aquifer.

The results of the study have provided much of the information needed for establishing the storage capacity of the entire system.

The Carmel Valley watershed drains about 255 square miles of terrain. The boundaries are considered impervious to flow, thus creating an enclosed basin whose only subsurface outlet for flow occurs at a narrow opening or crack containing porous alluvium below the mouth of the Carmel River.

There are two man-made reservoirs located at the Los Padres and San Clemente dams. The surface water capacity of the Los Padres reservoir is estimated at 3000 acre feet with a maximum surface area of 67 acres. The San Clemente reservoir surface storage is estimated at 2154 acre feet with a maximum surface area of 53 acres [Ref. 2].

The Los Padres dam is located approximately 6 miles upstream from the San Clemente dam. Levels at San Clemente reservoir are controlled by the regulation of spillage from Los Padres dam and by diversions from the reservoir by the California American Water Company to meet consumption demands. The drainage area above the San Clemente dam is about 125 square miles and although the upper subsurface is porous, there are no ground water basins. The lower Carmel Valley contains the remaining 130 square miles of drainage area, the runoff from which drains primarily into the Carmel River.

By far the major storage capacity for consumptive water is the Carmel Valley alluvium. It is estimated to extend 13 miles from the mouth of the Carmel River to a point about 1 mile south of the juncture of the Tularcitos creek and the Carmel river. According to the Dames and Moore study,

> The alluvium beneath the floor of the Carmel Valley ranges in width at its surface expression from 500 feet in upper valley areas to approximately 1 mile at the coast. It is generally less than one half mile wide. Its depth ranges from about 50 feet in upper valley areas to more than 150 feet in the lower valley near the coast. [Ref. 3]

The areal boundaries of the alluvium are estimated to include 4210 acres at the surface. The alluvium consists primarily of "sand and gravel, much of the gravel being boulder" [Ref. 2]. The results of the 1974 study suggest a total volume of the alluvium of 321,900 acre feet with an average thickness of 76.5 feet.

Individual drillers logs at various well sites were analyzed for specific yield[6] of the materials extracted. The specific yields ranged from .1946 to .2749 with a mean value of .2359. Thus the volume of extractable water during peak storage in the Carmel Valley aquifer can be estimated at 321,900 x .2359 = 75,936 acre feet. In December 1977 this estimate was revised upward for the western portion of the aquifer by the State Water Resources Board [Ref. 5].

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[6]Specific Yield = % of the total volume of the alluvium occupied by the ultimate volume of water that can be released from the saturated alluvium.

Although the report acknowledges over 78,000 acre feet of water that can be drawn from the full aquifer, this model will be based on the safe yield concept discussed by Hall & Dracup [Ref. 6]. Safe yield will refer to "that amount of water which can be withdrawn annually without causing an undesired influence in the basin" [Ref. 6]. There are three major factors that need to be considered when determining safe yield.

First, when an aquifer is drawn excessively low, the reduction in pressure of the water places a greater burden of the weight of the alluvium upon the alluvium itself. This causes grains and pebbles of the alluvium to shift resulting in tighter structure, reduced specific yield and less storage capacity. This phenomenon is known as land subsidence and is not considered a factor in the alluvium below the Carmel riverbed.

Second, long term use of an aquifer requires annual recharge from percolation of runoff due to rainfall. If annual extractions exceed the long term annual recharge capability of runoff, then over time the water table will be lowered. This phenomenom has caused damage to many valuable ground water tables in the past and only in recent years has there been careful monitoring of the long term balance between extraction and recharge.

The recharge rate of the Carmel Valley alluvium is remarkably rapid due to its high permeability. Recharge is accomplished

by percolation of stream flow of the Carmel river through the riverbed. Dames and Moore [Ref. 3] place percolation rates of the streambed as high as 100 cubic feet per square feet per second, while the Zone 11 study observed a recovery rate of "8 to 23 feet per month in November 1972 following the last dry period" [Ref. 5].

The 50 year mean annual full natural flow of the Carmel river at the San Clemente dam is estimated to be 61,900 acre feet. Consequently, the safe yield for maintenance of the water table is quite high, perhaps exceeding 50,000 acre feet.

Third, coastal aquifers face a unique problem when the alluvium extends beyond the seashore. In effect the alluvium is saturated below the land side with fresh water and below the ocean side with salt water. Within the alluvium there exists a boundary or face consisting of a mix of salt and fresh water. This boundary is maintained close to the shore line by the pressure of the water table which is elevated above sea level, producing a seaward flow of fresh water.

Sea water is heavier than fresh water. Should the height of the water table be reduced below certain levels, the heavier sea water could set up reverse flow landward beneath the fresh ground water. Since commercial wells are normally drilled the entire depth of the alluvium for maximum withdrawal, wells in such locations would no longer be of any use due to salt water contamination in their lower parts (see Figure 3).

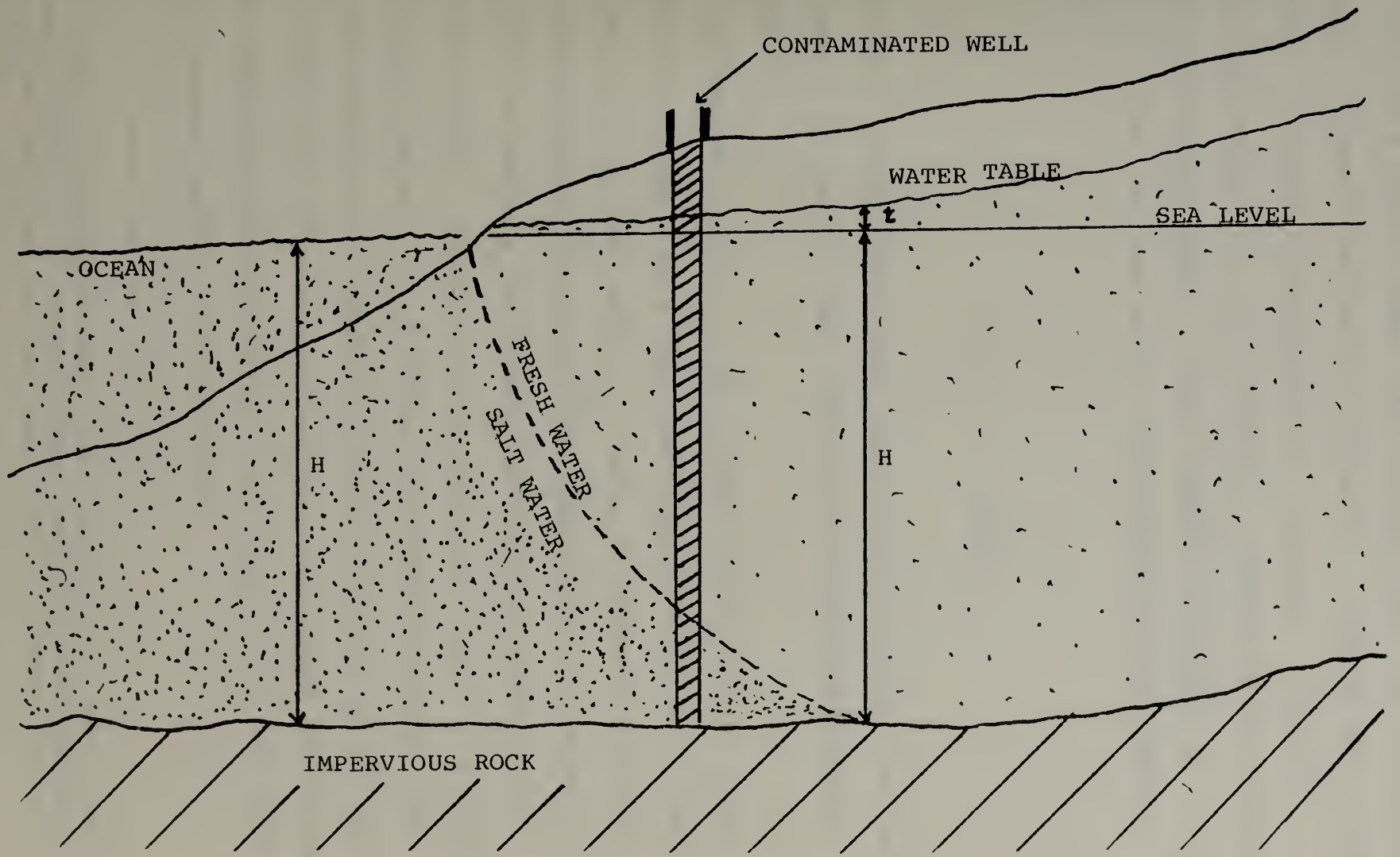
CONTAMINATED WELL
WATER TABLE
t
SEA LEVEL
OCEAN
H
FRESH WATER
SALT WATER
H
IMPERVIOUS ROCK

FIGURE 3

There is a simple thumb rule for the water table elevation required to prevent sea water intrusion. Consider the columns of water in Figure 3 represented by H and H+t. For H+t to be fresh water, it must be equal in weight to the column H of the heavier sea water. Using specific gravities of 1 and 1.025 for fresh and sea water, the following relationship holds:

$$(H+t) = 1.025\ H\ ,$$

or H = 40t, or for every foot that the water table lies above sea level, 40 feet of fresh water can be maintained below sea level.

The deepest portion of the Carmel Valley aquifer lies next to the coast. Well depth measurements indicate a maximum depth of 160 feet below sea level to impervious strata. The water table at the coastline, therefore, must be maintained at or above 4 feet above sea level to prevent sea water intrusion. This is by far the most restrictive requirement under the safe yield concept discussed earlier. That is, this model will consider the gross capacity of the aquifer to be that yield of the alluvium that lies above the minimum water table elevation required to preclude sea water intrusion, under present methods of extraction.[7]

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[7]There exist methods (most quite expensive) which enable inland lowering of a coastal water table while maintaining a pressure "barrier" at the coast line to prevent sea water intrusion.

This approach is considered quite conservative by some hydrologists as illustrated by the following comment by an engineer with the California State Water Resources board,

> Pumping the ground water until its levels are below sea level will not cause sea water intrusion as long as there exists a mound of fresh water with an elevation greater than sea level between the ocean and the area pumped. This could be done on a short time basis without injection barriers [Ref. 7].

Another report on ground water resources of the Carmel Valley was submitted by the Carmel Valley Master Plan Study Committee [Ref. 4]. It used the data from the Zone 11 study to construct cross sectional views of the alluvium in an effort to accurately determine what portion of the alluvium lay sufficiently above sea level to preclude sea water intrusion. The results were an alluvial volume of 116,214 acre feet which, given a permeability of .2359, computes to 27,500 acre feet of storage.

Total usable storage of the system, therefore, is 27,500 acre feet of ground storage plus 5,000 acre feet of surface storage in the reservoirs. This figure should be considered the most conservative estimate of maximum storage capacity of the watershed. There are many who claim the figure is considerably higher while there are still some who doubt it is that high. Some of the differences of opinion among the "experts" seem to be linked to differing points of view on what future growth should be permitted on the Monterey Peninsula, an issue totally irrelevant to this study.

This study will use 33,000 acre feet as the maximum static capacity for usable storage of water by the Monterey Peninsula watershed. It is static in the sense that this much water is extractable even after all runoff has ceased.

In the spring of the year when this model considers alternative decisions, the storage system may not be static, particularly if the previous rains were at or above normal levels. It is possible after heavy rainfall for stream flow to continue into the reservoirs and the Carmel riverbed as late as July. If the static storage on May 1^{st} is at maximum capacity, then there exists a period of simultaneous consumption and replenishment until all flows cease. This additional source of residual runoff after complete recharge will be modelled as "virtual" capacity above and beyond the maximum static capacity already discussed. The motivation for modelling it in this manner will be clarified in the following section.

B. REPLENISHMENT — A STATISTICAL MODEL OF RUNOFF

Several references texts and articles [Ref. 1,8,9,10,11, 12] were consulted for replenishment modelling techniques. Most of the hydrological models discussed utilized physical models of runoff. The physical characteristics of the alluvium are carefully studied, permeabilities established, runoff characteristics of the terrain are estimated, climatological data collected for coefficients of evaporation, types and density of ground vegetation analyzed to determine

evapotranspiration rates, suburban and urban development studied for their associated runoff characteristics, storm intensities estimated and their frequencies recorded, coefficients of storage, permeability and transmissibility estimated and many other physical properties explored.

From such data parameters are established that enable the hydrologist to simulate the behavior of the watershed using one of a variety of mathematical, physical and/or analog type models depending upon his objective. The parameters necessary for this type of modelling of the peninsula watershed are not available nor are they considered obtainable within the scope of this study.

More recently, studies in hydrology have applied statistical approaches to runoff models, particularly when the historical data base is available and the physical characteristics are not well known. The technique employs a fundamental relationship known as Hydrologic Balance which takes the following form:

INFLOW - OUTFLOW = CHANGE IN STORAGE

Elements of inflow and outflow are illustrated in Figure 4. According to Peters [Ref. 1], the specific basin balance may contain any or all of the following:

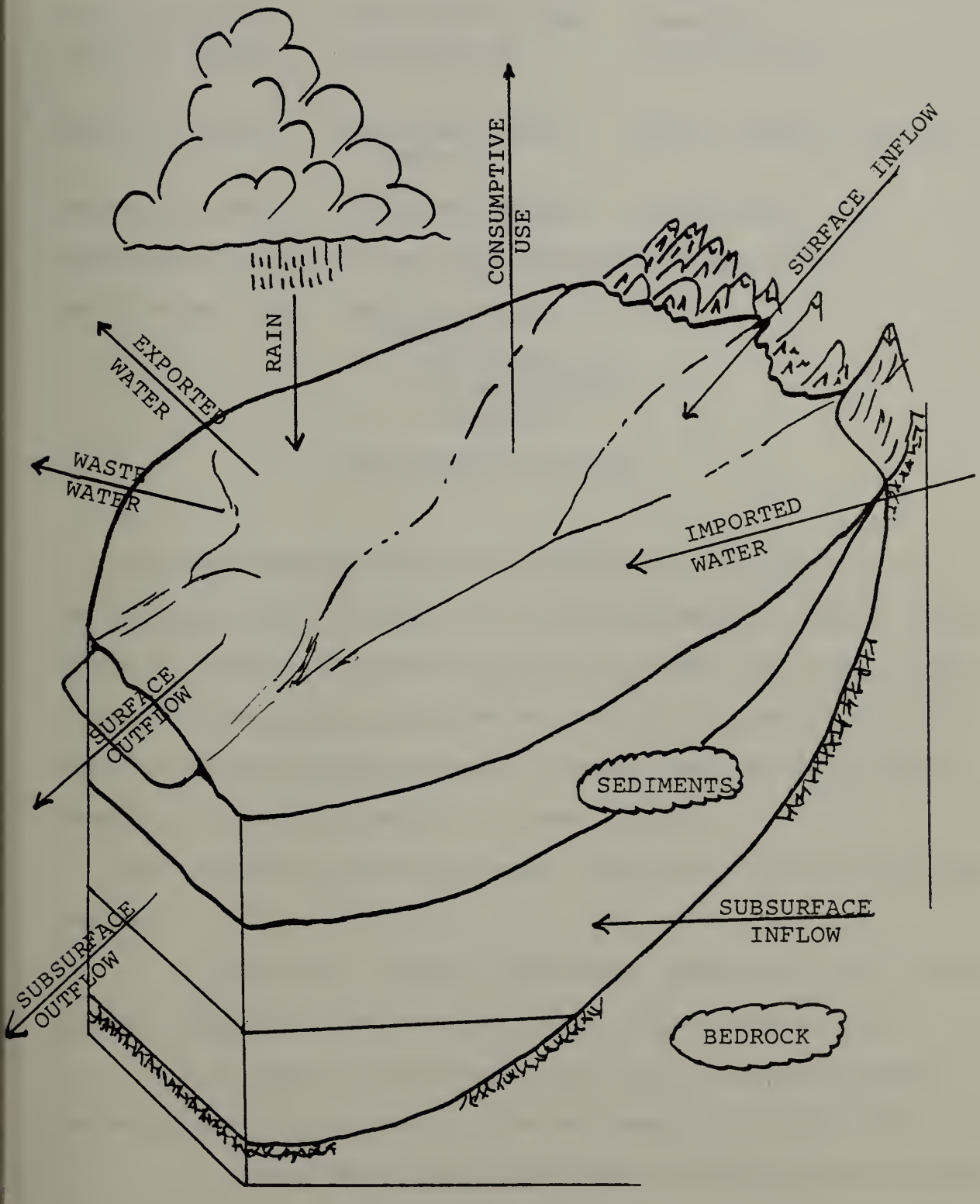
CONSUMPTIVE USE
SURFACE INFLOW
RAIN
EXPORTED WATER
WASTE WATER
IMPORTED WATER
SURFACE OUTFLOW
SEDIMENTS
SUBSURFACE INFLOW
SUBSURFACE OUTFLOW
BEDROCK

FIGURE 4

INFLOW	OUTFLOW	CHANGE IN STORAGE
Precipitation	Consumptive Use	Reservoirs
Surface stream inflow	Evaporation	Ground water
Imported water	Exported fresh water	Saline water intrusion
Imported sewage	Exported sewage	Subsidence
Subsurface inflow	Subsurface outflow	Perched water
Desalinated water	Surface stream outflow for irrigation for artificial recharge	
	Agricultural drains	

For the Monterey Peninsula watershed, the Hydrologic Balance was used to obtain accurate estimates of total inflow. Since all inflow is due ultimately to annual rainfall, total annual inflow data could then be compared to annual rainfall data in hopes of determining a function for estimating the unknown inflow as a result of known rainfall.

The following statistics were available from the indicated sources:

1. Monthly flows of the Carmel River at Carmel from annual reports of the U.S. Geological Survey [Ref. 13].

2. Rate of subsurface flow into the ocean as estimated by the California State Water Resources Board [Ref. 2].

3. Total diversions from the Los Padres/San Clemente Reservoirs from the records of the California American Water Company (Cal Am).

4. Total monthly extractions from the Carmel Valley aquifer by Cal Am as stated in their records.

5. Annual private consumption from the Carmel Valley aquifer as estimated by the California State Water Resources Board.

6. Monthly reservoir levels recorded by Cal Am.

7. Annual average change in well levels in the Carmel Valley aquifer from the records of the Monterey Flood Control and Water Conservation District [Ref. 14].

The data was collected by water year defined as 1 October through 30 September in order to insure as static a reading of the system as possible. In the Carmel Valley, rainfall occurs between the months of October and April with little or no rain throughout the summer, so that by 1 October all runoff can be considered complete. This provides the most accurate computation of runoff following a winter rain. Unfortunately complete records have been kept only since 1963. They are shown in Table II.

The computation of runoff was done as follows: Runoff (Inflow) = Change in storage plus Outflow, where Change in storage = Change in Reservoirs plus change in ground water and Outflow = (Carmel River flow at Carmel) plus (subsurface flow at Carmel) plus (Reservoir diversion by Cal Am) plus (Well production by Cal Am) plus (Private Well production). The resulting runoff computations are tabulated in Table III by year with the year's corresponding rainfall total at Los Padres dam.

Water Year	Stream Flow at River Mouth	Subsurface Flow at Mouth	Production by Cal Am	Change in ground water	Change in Reservoirs	Other Consumption
76-77	0	130	6,831	- 5,462	- 93	2,700
75-76	180	130	12,257	-10,031	-1462	2,700
74-75	94,600	130	11,585	- 2,185	+ 229	2,700
73-74	87,810	130	11,311	- 1,192	+ 546	2,700
72-73	150,400	130	11,302	+ 1,390	+1155	2,700
71-72	7,000	130	11,892	+ 3,973	- 877	2,700
70-71	30,320	130	11,193	- 3,774	+ 19	2,700
69-70	50,140	130	12,097	- 3,277	- 866	2,700
68-69	226,300	130	10,854	+ 4,270	+1773	2,700
67-68	7,430	130	12,054	- 2,383	-1779	2,700
66-67	128,900	130	10,514	+ 99	+1890	2,700
65-66	23,700	130	(11,371)*	+ 298	(- 917)	2,700
64-65	49,480	130	(10,963)	+ 1,103	(+ 201)	2,700
63-64	21,270	130	(10,281)	- 1,808	(-1294)	2,700
62-63	92,770	130	(9,945)	+ 596	(+1494)	2,700

* Parentheses Indicate Estimate Based on Calendar Year Data

Table II

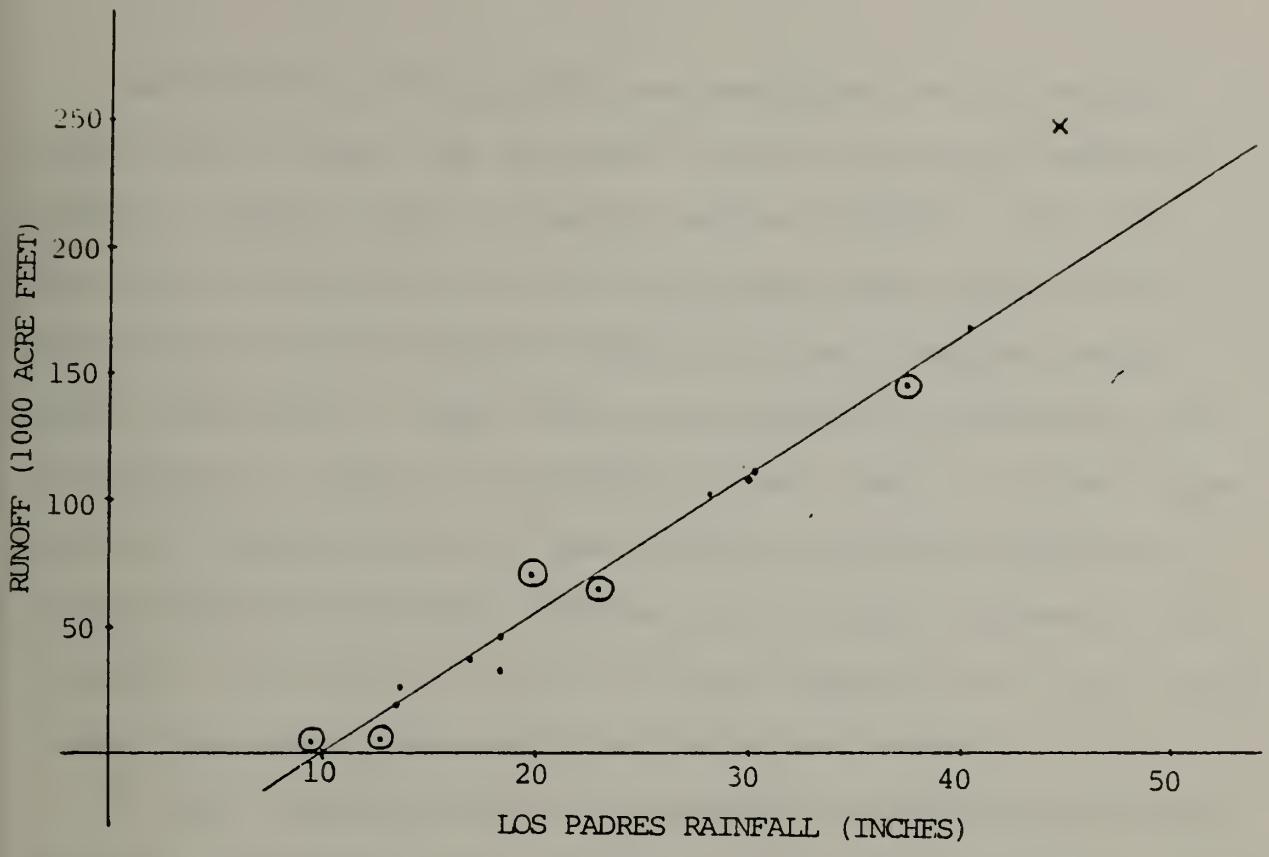

Figure 5

Water Year	Runoff	Rainfall at Los Padres
76-77	4106	12.77
75-76	3774	9.47
74-75	107,059	30.11
73-74	101,305	28.18
72-73	167,077	40.62
71-72	24,818	13.78
70-71	40,588	18.42
69-70	60,924	19.9
68-69	246,035	44.89
67-68	18,153	13.59
66-67	144,233	37.47
65-66	37,282	17.12
64-65	64,577	23.08
63-64	31,279	18.59
62-63	107,635	30.9

Table III

Exploratory data analysis was performed on the runoff and rainfall data, the results of which were quite promising. Figure 5 shows a plot of Runoff versus Rainfall. The plot has definite structure with an apparent linear relationship except for the 1969 runoff figure that was recorded during flood conditions. That value was subsequently discarded for two reasons. First, it is highly likely that it is the least accurate value in view of the flooding that occurred when measurements were taken. Second, the primary concern is for accurate estimates of normal to below normal runoff since near flood conditions will easily recharge the system.

A least squares fit of the remaining runoff versus annual rainfall produces a good model in a statistical sense; however there are certain qualities of the runoff data revealed in Figure 5 that imply additional dependency. All the circled points which lie above the fitted line have something in common. They all represent values that occurred in a year following a previous year of above average runoff. On the other hand the circled points lying below the line represent values which occurred following a year of below average runoff. This suggests that previous runoff has an impact on current runoff.

A multiple regression of runoff as a function of rainfall and the one year lag of runoff produced slightly better statistics and far better parallels of the trends of the actual data. Unfortunately the decision model's state vector now

has two dimensions (Rainfall, Previous Runoff), each of which has considerable range. A simple heuristic approach was tried to reduce the number of states required overall.

Assume that annual runoff depends not only upon the amount of annual rainfall but also upon the wetness of the soil prior to the rainy season. Furthermore, assume that condition of the soil can be categorized in broad terms as dry, normal or wet (called wetness). Now the second dimension of the state vector, namely wetness, need only range over three values.

The following heuristic gave the best results. Let wetness, W_n, be 1, 2, or 3 corresponding to dry, normal and wet soil conditions. The value of W_n is found from the previous years runoff as follows:

$$\text{Wetness} = \begin{cases} 1 & \text{If the previous runoff was less than 11,601 acre feet (one standard deviation below the mean}^8\text{)} \\ 3 & \text{If the previous runoff was greater than 148793 acre feet (one standard deviation above the mean)} \\ 2 & \text{Otherwise} \end{cases}$$

The resulting model which is presented below far exceeded expectations in accuracy and estimating power:

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[8]The mean and standard deviation referred to are the sample mean and deviation computed from all the runoff data available.

Runoff = 5296 (Rain) + 8433 (Wetness) - 71,059 Acre feet

except that in no case is runoff estimated to be less than zero.

Figure 6 shows a plot of actual Runoff vs the estimated Runoff by the model.

C. VIRTUAL CAPACITY

The above model owes much of its accuracy and simplicity to the selection of October as the start of the annual period, enabling an accurate estimate of runoff with only two pieces of information required; annual rainfall for the year and wetness.

Since streamflow can continue for some time after heavy rainfall has ceased, it is possible for the reservoirs and the alluvium to continue recharging for some time after the first of May, the date marking the beginning of the decision period. What this amounts to is additional storage of sub-surface flows that have not yet been removed by stream flow to the ocean. This additional storage, called "virtual storage", is considered available only during May, June and July. Therefore the most that it could ever be is the maximum expected demand from the system during these months. Historically this amounts to about 5,000 acre feet.

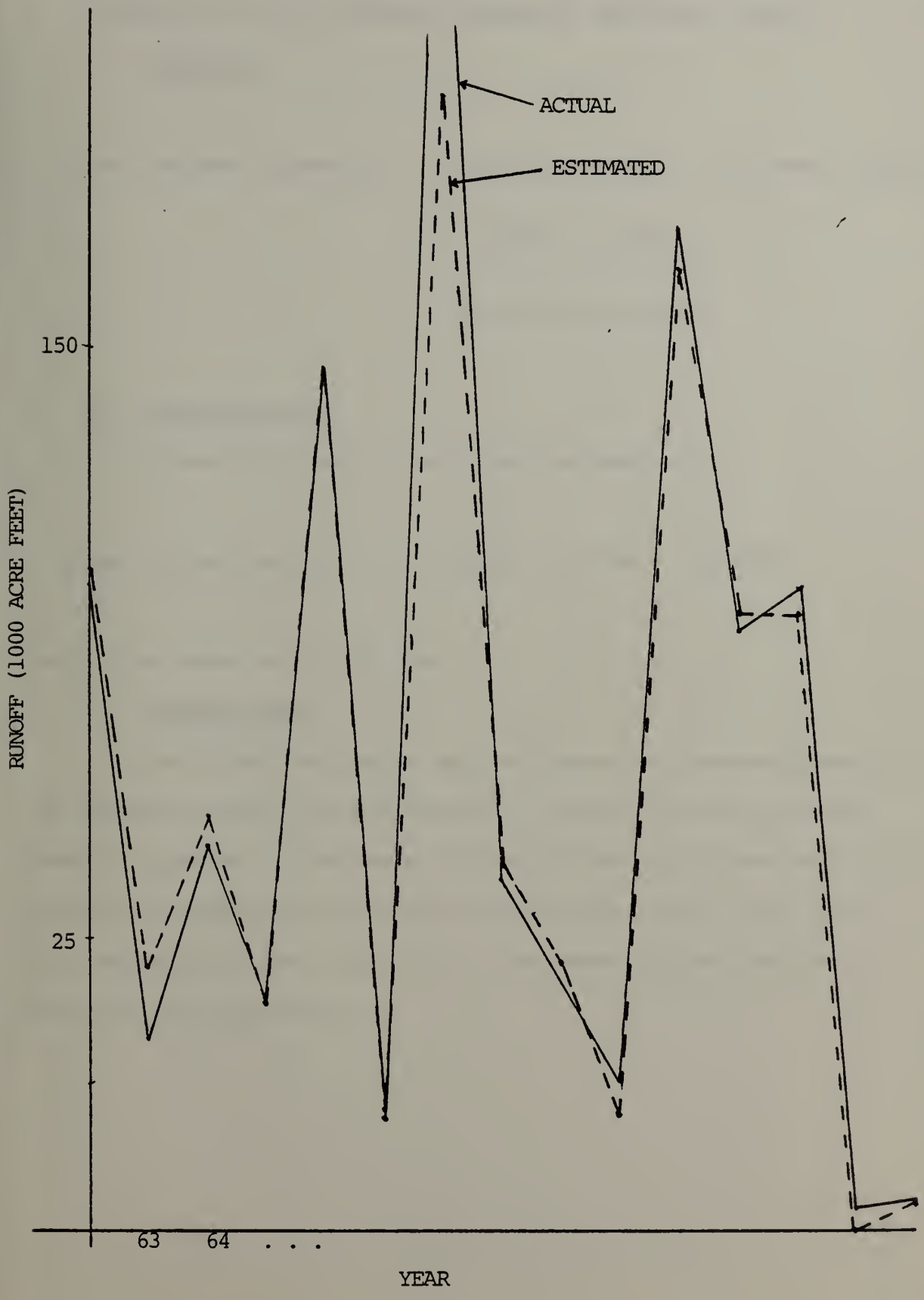

FIGURE 6

D. SUMMARY OF THE MONTEREY PENINSULA WATERSHED MODEL

1. Capacity

1 May Maximum Capacity = Static Capacity + Virtual Capacity

= 33,000 + 5,000

= 38,000 acre feet

2. Replenishment

Given R inches of rain and wetness = W,

Total Annual Runoff = $5296 \cdot R + 8433 \cdot W - 71,059$;

but in no case less than zero.

3. Seaside Area

The data available and the amount of water drawn from the Seaside wells did not justify a similar model of the Seaside aquifer. The Zone 11 investigation places safe yield figure for Seaside at 2,200 acre feet per year [Ref. 2]. This study will treat that as a constant annual import of water to the peninsula.

IV. THE OBJECTIVE FUNCTION — AN EXPERIMENTAL DETERMINATION OF UTILITY

The objective of this model is directly related to the value that water has to the residents. A naive approach would be to assume that twice as much water should provide twice as much value. If this were the case it would not be hard to see that the solution to the problem is to consume all water as soon as it becomes available. But is this a reasonable argument? It is equivalent to saying that out of 100 gallons of water made available, the second fifty gallons provides the same amount of value that would have been provided by only having 50 gallons to begin with. Most will agree that this is not true; that the value of water per unit volume decreases as total amount of water available increases. Hence the need for a utility function to provide an index of how the value of water changes as more becomes available. Reference 15 presents an excellent review of utility theory and experimental procedures for obtaining information about individual utility. This study assumes that a utility function for water exists for residents of the Monterey Peninsula. What the model needs is an indexing function that will assign to the amount of water D some index U(D) that will permit comparisons in utilities of various alternatives.

Since the origin and unit of the utility scale can be assigned arbitrarily, one can select any 2 alternatives from

a given set of alternatives and assign fixed values of utility to them. Then, through the use of proposed "lotteries" involving those 2 alternatives, individuals may be induced to reveal on the same utility scale, their utility of some of the other alternatives available.

An experiment based upon this concept was conducted in the form of a survey among several faculty members of the Naval Postgraduate School who were also residents of the Monterey Peninsula.

A set of alternatives was presented to each member questioned. Each alternative represented a fixed per person daily consumption limit to which the population would be restricted for an extended period. The alternatives ranged on a continuous scale from a strict rationing value of 50 gallons per person per day (gpd) to unrestricted consumption (arbitrarily set at 200 gpd).

Four different lotteries were then presented using mixtures of the 2 extreme alternatives 50 and 200. Those questioned were asked to provide the single alternative that they would consider equivalent to the given lottery.

Computation of utilities was accomplished by fixing the utility of 50 gpd at 0 and the utility of 200 gpd at 100. For each lottery such that 50 gpd occurred with probability p and 200 with probability 1-p, the utility of the lottery is simply $pU(50) + (1-p)\,U(200) = (1-p)(100)$. Thus a utility value for each answer given could be assigned on the basis of the equivalent lottery.

The particular lotteries presented yielded those alternatives whose utilities were 50, 60, 80 and 90 which together with 0 and 100 already fixed gave 6 data points with which to estimate the utility function. The resulting utility function was constructed using the median responses to the survey to reduce the influence of poorly answered questionaires.

Figure 7 shows the points that resulted from the survey. The curve in the figure represents a close smooth approximation to the utility function. The equation of the curve is given by:[9]

$$U(D) = \begin{cases} (1.617)D - 80.105 & \text{for } D < 65 \text{ gpd} \\ (79.154)\sqrt{D} - (37.129)\ \text{Ln}\ D & \text{for } 65 \leq D \leq 175 \text{ gpd} \\ -(2.72)D - 281.354 & \\ (.0595)D + 87.83 & \text{for } 175 < D \leq 200 \text{ gpd} \end{cases}$$

A complete copy of the survey is provided in Appendix B.

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[9] Empirical data was created from a smooth fit drawn through the survey points and multiple regression applied to the sum of appropriately shaped curves (parabola, line and logarithm). Both ends were then refined by attaching smooth linear extensions.

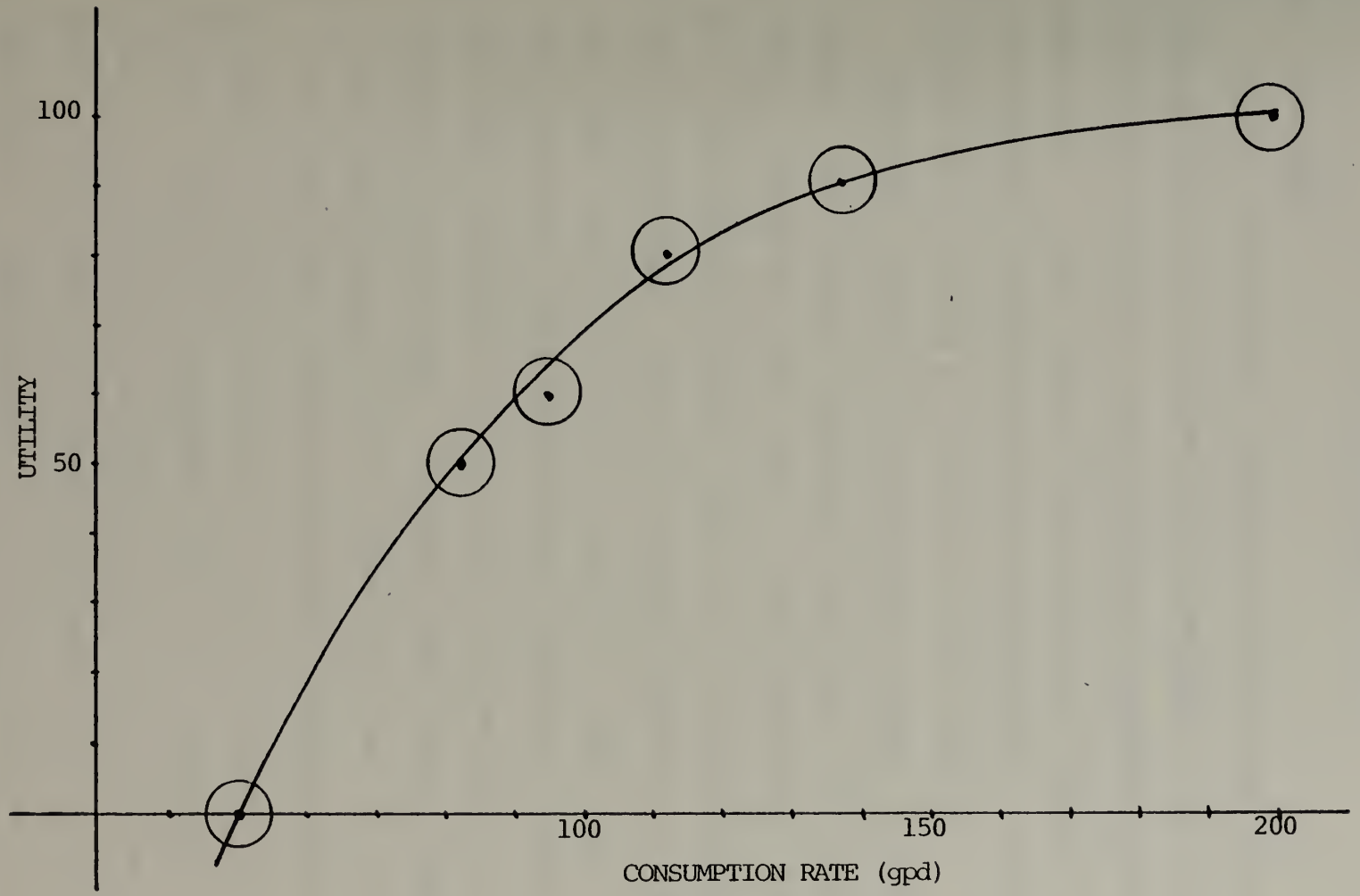

FIGURE 7

V. EXERCISING THE MODEL

A. THE MODEL

Coding of the model was done in Fortran IV programming language for use on an IBM 360/67 computer. The output was designed to provide a chart which the decision maker could enter with a 1 May state of the system and extract the optimal decision for the next year's consumption. A copy of the program can be found at the end of this study.

The model itself is discrete with respect to the storage supply, the feasible consumption decisions and rainfall. Storage values are described in 1,000 acre feet increments up to the maximum capacity, each with three possible conditions of wetness. Thus for a maximum capacity of 38,000 acre feet, there are 117 possible states for entry into the chart. The permissible decisions for each state are also in 1,000 acre feet increments ranging from 0 to the amount in storage indicated by that state. Rainfall was likewise made discrete to facilitate computation of expected values of utility.

Utilities are computed using the function derived earlier as typical for each resident of the peninsula. Since the utility function is dependent upon net consumption by an individual, a conversion is required from the decision in acre feet to the number of gallons per person per day that it represents. Approximately 5% of all production is lost to waste before metering by Cal Am and only 86% of metered

production goes to residential use. In addition the model assumes an automatic importation of 2,200 acre feet from the Seaside aquifer. The current population figure used by the model is 91,000 residents serviced by Cal Am. Therefore for a given decision D of acre feet to consume, only $\frac{(7.5)(43,560)}{(365)(91,000)}$ (.95)(.86) (D-2840+2200) gpd is available for consumption; where 7.5 = # gal per cubic ft, 43,560 = # cubic feet per acre feet and 2840 = # acre ft of private well extraction and subsurface losses which are assumed uncontrollable.

B. ASSUMPTIONS

The following assumptions were made to facilitate the running of the model. Some are obviously not true in an exact sense but at the same time they are not expected to disrupt the accuracy to any significant degree.

Assumption 1: Runoff is assumed to recharge the aquifer instantly. That is, if there is sufficient capacity left in the alluvium to hold the computed runoff, then it will all percolate into the aquifer before reaching the ocean.

Assumption 2: Given the opportunity to consume water, the population will consume it. This assumption is made more realistic by bounding production by the maximum historical figures from recent normal consumption. The model essentially stops considering any decisions that would provide more extraction than the population would freely consume. Figure 8 shows a normal consumption pattern under no restrictions. A production limit of 20,000 acre feet is placed on the model to

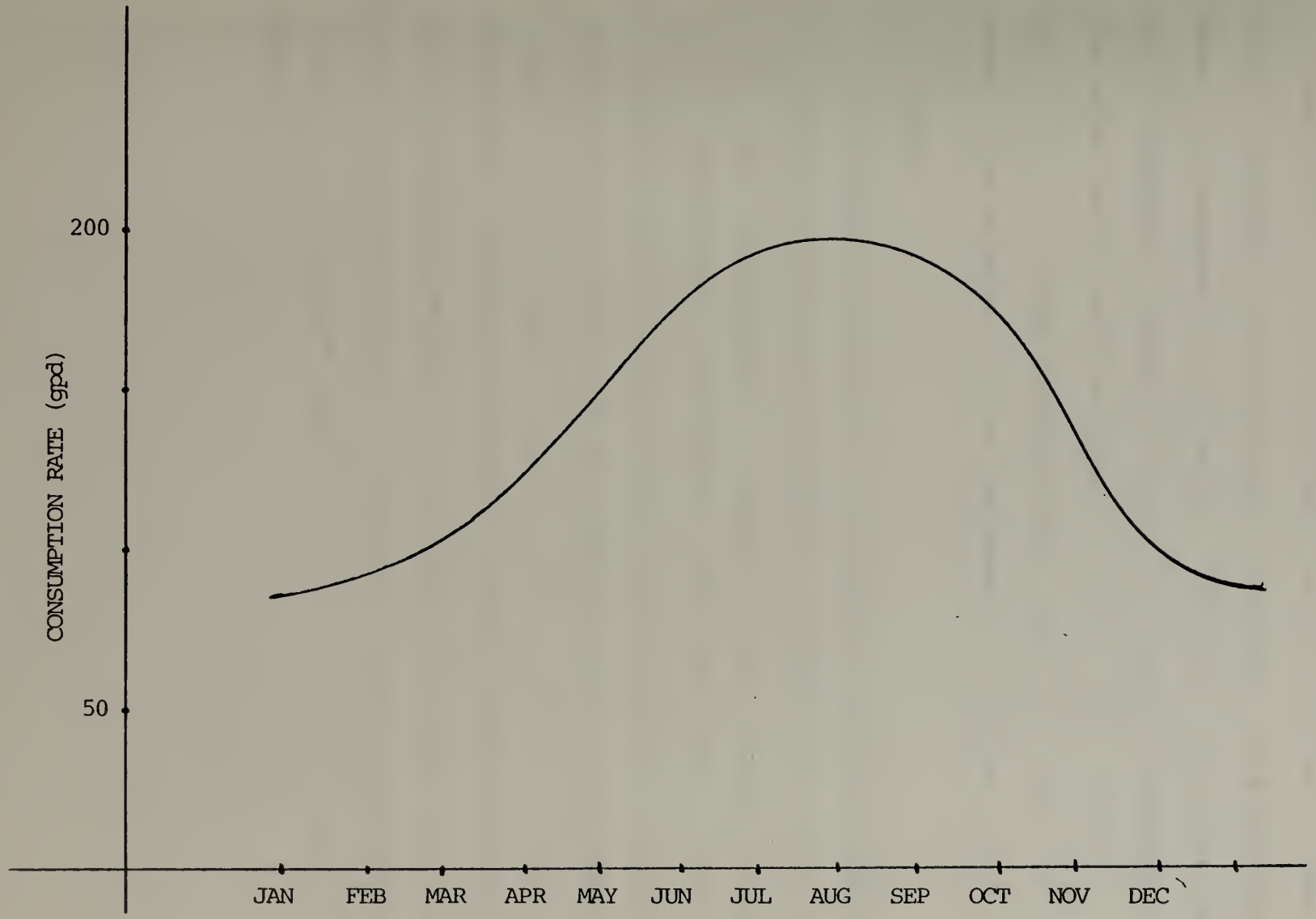
200
50
CONSUMPTION RATE (gpd)
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

FIGURE 8

preclude average daily per capita consumption that would exceed that pattern.

Assumption 3: It is assumed that the California American Water Company has the capability of meeting the production demands recommended by the model. That is, given that the model recommends a certain figure for optimal consumption, the water company will be able to produce that quantity. The 1975-1977 drought revealed that this is in fact not the case. This problem will be discussed in the last section.

C. RESULTS

The output of the model is presented following Appendix B. All possible states are represented. There are 3 pages of output, each representing a separate initial wetness condition. One selects dry, normal or wet as a result of the current estimate of annual runoff due to current rainfall (since stream flow may not be complete, this can be estimated using the runoff model of Section III). Find the column whose first row entry equals the current estimated state and read the optimal decision in acre feet in column 2 and the optimal rationing policy in column 4. Column 3 contains the value of the objective function due to the particular optimal decision.

VI. CONCLUSIONS AND FURTHER OBSERVATIONS

A. CONCLUSIONS

A careful study of the results of the model reveal that the optimal decision is always to consume all available supply when that supply falls below the normal unrestricted consumption established by past experience. The result is not surprising in view of the normal hydrologic cycle for the area.

With a virtual capacity conservatively estimated at 38,000 acre feet and average annual runoff in excess of 60,000 acre feet, the model has reason to be optimistic about future replenishment of supplies. This optimism coupled with the rather mild rate of change in the slope of the utility function is responsible for the conclusion reached.

This does not imply that there is no need for rationing during consecutive years of drought. It merely implies that under the conditions of the model, there is nothing to be gained by sacrificing present consumption to add to future supplies. If current supplies are low, of course, rationing is called for to preclude running out in the current year.

B. FURTHER OBSERVATIONS

An interesting fact was brought out by the model. According to records, the 1974-75 runoff was above average. Assuming 38,000 acre feet in storage on 1 May 1975 and computing forward from the data available, the amount of storage on 1 May, 1977

was estimated to have been about 16,500 acre feet. The model recommends consuming all which equates to a rate of 125 gpd for the year. Why then did Cal Am impose strict rationing of 50 gpd?

The answer to this question requires re-examination of the extent of the Carmel Valley alluvium. Figure 9 shows a vertical cross-section of the aquifer along with the boundaries of the Cal Am well fields and elevation of the water table during and after the drought.

Since supplies were considerably below normal in early winter of 1977, the major source of production by Cal Am would necessarily come from their wells. Normal well production was fully restored in Feb. 1978 at 12,760 gal per minute. This compares with the early December 1977 maximum rate of 1630 gal per minute. Figure 9 illustrates the reason for the drastic reduction in extraction capability.

The December 1977 level of the water table, although not excessively low throughout, was less than 50% of normal levels in the region of the aquifer containing the Cal Am well fields. As a result, production capacity of the Carmel Valley alluvium was limited to less than 3,000 acre feet per year. Anticipation of only 3,000 acre feet plus best estimates of an additional 4,000-5,000 acre feet of combined production from Seaside and the reservoirs prompted the decision by Cal Am.

The obvious solution to this problem after observing Figure 9 is to place wells in the western most portion of the

CROSS-SECTION OF C.V. ALLUVIUM (NOT TO SCALE)

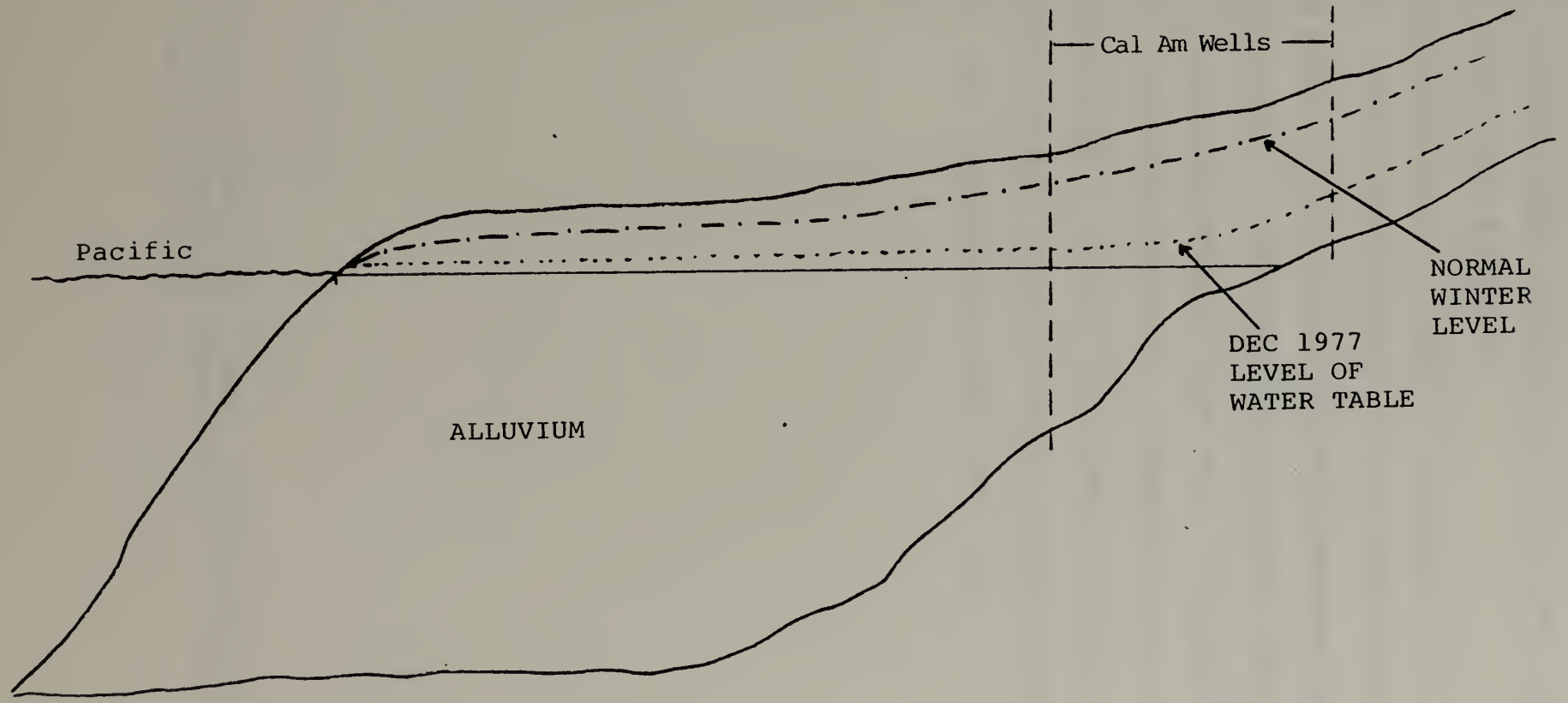

FIGURE 9

aquifer. This has been proposed and will most likely be resolved in the near future.[10]

A final observation is offered concerning the controversial topic of the future growth of the Carmel Valley/Monterey peninsula area; in particular how the increased demands for water will be met. According to the runoff model derived earlier, water needs of the future will be supplied in great quantity. The deficiency lies in adequate storage. At present an average of 60,000 acre feet of stream flow is lost to sea each year, runoff which if stored could provide more than twice the present demand for water.

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[10]There are questions of water quality that enter here which although solvable do have an impact on questions of where to locate new wells.

APPENDIX A

MATHEMATICAL REPRESENTATION OF THE MODEL

Let:

n = subscript indicating the number of years remaining in the time horizon selected for optimization

α = discount factor $\quad 0 \leq \alpha \leq 1$

$\vec{X}_n$ = (x_n, w_n) = State vector composed of
x_n = amount of water in storage and
w_n = wetness condition of the soil

r_n = total annual rainfall, a random variable

$V_n(\vec{X}_n)$ = Optimal value of the objective function given the state $\vec{X}_n$

$U(D)$ = utility of Dgpd of water consumption

D_i = a feasible consumption decision

C = maximum storage capacity for water

$R(r,w)$ = runoff due to r inches of rainfall under conditions of wetness = w

The model was solved recursively using dynamic programming techniques as follows:

Let

$V_o(\vec{X})$ = 0 (there is no utility if there is no time)

then

$$V_1(\bar{X}_1) = \max_{0 \le D_i \le X_1} (U(D_i) + \alpha E[V_o(\bar{X}_o)] = \max_{0 \le D_i \le X_1} [U(D_i)]$$

and given $V_n(\vec{X}_n)$, the model computes $V_{n+1}(X_{n+1})$ as follows:

$$V_{n+1}(\vec{X}_{n+1}) = \max_{0 \le D_i \le X_{n+1}} \{U(D_i) + \alpha E[V_n(\vec{X}_n)]\}$$

where

$$\vec{X}_n = \min[C; X_{n+1} - D_i + R(r_n, w_n)]$$

and

$E[S]$ "Expected Value" of S.

The values of parameters used were:

$C = 38{,}000$ acre feet

$\alpha = .9$

$R(r,w) = \max\{5296r + 8433w - 71{,}058; 0\}$

and

$$w_n = \begin{cases} 1 & \text{if } R(r_{n-1}, w_{n-1}) < 1160 \text{ acre feet} \\ 2 & \text{if } 1160 \le R(r_{n-1}, w_{n-1}) \le 148793 \text{ acre feet} \\ 3 & \text{if } 148{,}793 < R(r_{n-1}, w_{n-1}) \end{cases}$$

The selection of a value for n can be somewhat arbitrary. Since future utilities are discounted, there should be some value of n beyond which the solution becomes independent of n.

APPENDIX B

THE SURVEY

The following survey is being conducted to determine the value of water to the population of the Monterey Peninsula. More specifically, as the amount of water for consumption increases, what is the relative increase in value to the consumer? The results will be used in a thesis study at the operations research dept. of NPS.

The basic unit of measure for water consumption will be expressed in gallons per person per day (gpd); however, compliance with consumption restrictions will be monitored monthly. Consumption restrictions (rationing) are set each year for the entire year and can range from a minimum (strict) of 50 gpd on up to 200 gpd (considered unrestricted).

Consider the time period from now through the next 10 years. You will be presented with an expected rationing pattern over those ten years that evenly distributes a given number of strict rationing years among years with no consumption restrictions whatsoever. On the right please enter the fixed rationing policy that you consider to be equivalent in value for you.

For Example:

Policy A		Policy B
8 years at 50 gpd and 2 years unrestricted	or	10 years of continuous rationing fixed at 60 gpd.

Indicates that you are indifferent between rationing at 60 gpd 100 percent of the time and rationing at 50 gpd 80 percent of the time.

Attached to the survey you will find some relevant statistics and current usage information that should be of considerable value in determining your choices.

Upon completion please fold and place the survey in the guard mail for forwarding. Thank you.

QUESTIONNAIRE

I. For this section please enter the rationing value in Policy B which will cause you to be indifferent between Policy A and Policy B.

	Policy A		Policy B
1.	5-years of strict rationing at 50 gpd and 5 years of unrestricted consumption	OR	10 years of continuous rationing fixed at _____ gpd
	Policy A		Policy B
2.	4 years of strict rationing at 50 gpd and 6 years unrestricted consumption	OR	10 years of continuous rationing fixed at _____ gpd
	Policy A		Policy B
3.	2 years of strict rationing at 50 gpd and 8 years unrestricted consumption	OR	10 years of continuous rationing fixed at _____ gpd
	Policy A		Policy B
4.	1 year of strict rationing at 50 gpd and 9 years unrestricted consumption	OR	10 years of continuous rationing fixed at _____ gpd

II. For this section please enter the values that you feel the majority of local residents would enter if asked.

	Policy A		Policy B
1.	5-years of strict rationing at 50 gpd and 5 years of unrestricted consumption	OR	10 years of continuous rationing fixed at _____ gpd
	Policy A		Policy B
2.	4 years of strict rationing at 50 gpd and 6 years unrestricted consumption	OR	10 years of continuous rationing fixed at _____ gpd
	Policy A		Policy B
3.	2 years of strict rationing at 50 gpd and 8 years unrestricted consumption	OR	10 years of continuous rationing fixed at _____ gpd
	Policy A		Policy B
4.	1 year of strict rationing at 50 gpd and 9 years unrestricted consumption	OR	10 years of continuous rationing fixed at _____ gpd

GENERAL INFORMATION

I. STATISTICS

CONSUMPTIVE ACTION	QUANTITY OR RATE OF CONSUMPTION
A. FILLING AVERAGE TUB	30 Gals
B. FLUSHING TOILET	5 Gals
C. 5 MINUTE SHOWER	30 Gals (6 Gals/min)
D. DISHWASHER (ONE LOAD)	15 Gals
E. AUTOMATIC CLOTHES WASHER	
1. MINIMUM LOAD	25 Gals
2. MAXIMUM LOAD	50 Gals
F. KITCHEN FAUCET	6 Gals/min
G. COMMON GARDEN HOSE	250 Gals/hr
H. COMMON LAWN SPRINKLER	120 Gals/hr

II. Personal Hygiene requirements for an adult range from an estimated minimum of 21 gals/day to an extravagant maximum in excess of 75 gals/day. A reasonable figure under normal conditions is about 45 gals/day. This figure accounts for drinking, bathing and hygiene only.

III. Consumption data from Cal-Am Water Company indicates that during the normal years preceeding the 1975-77 drought, the consumption of water by local residents varied from a rainy winter season low rate of about 85 gpd to a late summer high of about 175 gpd. The difference is due primarily to outdoor uses of water. Particularly maintenance of lawns and gardens.

For example, the recommended rate of water application for a healthy lawn is 1 inch per week for the coastal slopes and 1.5 inches per week for the inland coastal areas of central California.

Note: 1 in/wk on 5000 sq ft (~1/8 acre) = 3125 gal/wk = 446 gal/day. This equates to over 110 gpd for a family of four.

To prevent a lawn from dying during drought conditions, one is recommended to water for a minimum of 15 minutes per week. For the same 5000 sq ft of lawn, this amounts to 105 gals/week or 15 gals/day.

Recall that gpd refers to gals per person per day.

RESULTS WHEN INITIAL CONDITIONS ARE DRY

WATER ON HAND:	0.	1000.	2000.	3000.	4000.	5000.	6000.	7000.	8000.	9000.	10000.	11000.
OPTIMAL CONSUMP:	0.	1000.	2000.	3000.	4000.	5000.	6000.	7000.	8000.	9000.	10000.	11000.
TOTAL UTILITY:	398.	403.	416.	429.	442.	455.	468.	481.	494.	507.	519.	529.
GAL/PERSON/DAY:	0.	3.	11.	19.	27.	35.	43.	51.	59.	67.	75.	83.

WATER ON HAND:	12000.	13000.	14000.	15000.	16000.	17000.	18000.	19000.	20000.	21000.	22000.	23000.
OPTIMAL CONSUMP:	12000.	13000.	14000.	15000.	16000.	17000.	18000.	19000.	20000.	20000.	20000.	20000.
TOTAL UTILITY:	537.	545.	552.	557.	562.	566.	569.	572.	574.	575.	576.	577.
GAL/PERSON/DAY:	91.	99.	107.	115.	123.	131.	140.	148.	156.	156.	156.	156.

WATER ON HAND:	24000.	25000.	26000.	27000.	28000.	29000.	30000.	31000.	32000.	33000.	34000.	35000.
OPTIMAL CONSUMP:	20000.	20000.	20000.	20000.	20000.	20000.	20000.	20000.	20000.	20000.	20000.	20000.
TOTAL UTILITY:	578.	579.	580.	580.	581.	582.	583.	583.	584.	584.	584.	585.
GAL/PERSON/DAY:	156.	156.	156.	156.	156.	156.	156.	156.	156.	156.	156.	156.

WATER ON HAND:	36000.	37000.	38000.
OPTIMAL CONSUMP:	20000.	20000.	20000.
TOTAL UTILITY:	585.	585.	585.
GAL/PERSON/DAY:	156.	156.	156.

RESULTS WHEN INITIAL CONDITIONS ARE NORMAL

WATER ON HAND:	0.	1000.	2000.	3000.	4000.	5000.	6000.	7000.	8000.	9000.	10000.	11000.
OPTIMAL CONSUMP:	0.	1000.	2000.	3000.	4000.	5000.	6000.	7000.	8000.	9000.	10000.	11000.
TOTAL UTILITY:	403.	408.	421.	434.	447.	460.	473.	486.	499.	512.	523.	534.
GAL/PERSON/DAY:	0.	3.	11.	19.	27.	35.	43.	51.	59.	67.	75.	83.

WATER ON HAND:	12000.	13000.	14000.	15000.	16000.	17000.	18000.	19000.	20000.	21000.	22000.	23000.
OPTIMAL CONSUMP:	12000.	13000.	14000.	15000.	16000.	17000.	18000.	19000.	20000.	20000.	20000.	20000.
TOTAL UTILITY:	542.	550.	556.	562.	567.	571.	574.	577.	579.	579.	580.	581.
GAL/PERSON/DAY:	91.	99.	107.	115.	123.	131.	140.	148.	156.	156.	156.	156.

WATER ON HAND:	24000.	25000.	26000.	27000.	28000.	29000.	30000.	31000.	32000.	33000.	34000.	35000.
OPTIMAL CONSUMP:	20000.	20000.	20000.	20000.	20000.	20000.	20000.	20000.	20000.	20000.	20000.	20000.
TOTAL UTILITY:	581.	582.	582.	583.	583.	584.	584.	584.	585.	585.	585.	585.
GAL/PERSON/DAY:	156.	156.	156.	156.	156.	156.	156.	156.	156.	156.	156.	156.

WATER ON HAND:	36000.	37000.	38000.
OPTIMAL CONSUMP:	20000.	20000.	20000.
TOTAL UTILITY:	585.	586.	586.
GAL/PERSON/DAY:	156.	156.	156.

RESULTS WHEN INITIAL CONDITIONS ARE WET

WATER ON HAND:	0.	1000.	2000.	3000.	4000.	5000.	6000.	7000.	8000.	9000.	10000.	11000.
OPTIMAL CONSUMP:	0.	1000.	2000.	3000.	4000.	5000.	6000.	7000.	8000.	9000.	10000.	11000.
TOTAL UTILITY:	407.	411.	424.	437.	450.	463.	476.	489.	502.	515.	527.	537.
GAL/PERSON/DAY:	0.	3.	11.	19.	27.	35.	43.	51.	59.	67.	75.	83.

WATER ON HAND:	12000.	13000.	14000.	15000.	16000.	17000.	18000.	19000.	20000.	21000.	22000.	23000.
OPTIMAL CONSUMP:	12000.	13000.	14000.	15000.	16000.	17000.	18000.	19000.	20000.	20000.	20000.	20000.
TOTAL UTILITY:	546.	553.	560.	566.	570.	574.	578.	580.	582.	583.	583.	583.
GAL/PERSON/DAY:	91.	99.	107.	115.	123.	131.	140.	148.	156.	156.	156.	156.

WATER ON HAND:	24000.	25000.	26000.	27000.	28000.	29000.	30000.	31000.	32000.	33000.	34000.	35000.
OPTIMAL CONSUMP:	20000.	20000.	20000.	20000.	20000.	20000.	20000.	20000.	20000.	20000.	20000.	20000.
TOTAL UTILITY:	584.	584.	584.	585.	585.	585.	585.	585.	586.	586.	586.	586.
GAL/PERSON/DAY:	156.	156.	156.	156.	156.	156.	156.	156.	156.	156.	156.	156.

WATER ON HAND:	36000.	37000.	38000.
OPTIMAL CONSUMP:	20000.	20000.	20000.
TOTAL UTILITY:	586.	586.	586.
GAL/PERSON/DAY:	156.	156.	156.

```
      COMMON VN(3,3,70),PRODUC,CAPAC,POPUL
      EXTERNAL UTILS, RUNOFF,CONVER
      INTEGER DIMEN
      POPUL=91000.
      CAPAC=38000.
      PRODUC=20000.
      DIMEN=IFIX(CAPAC/1000.+1.5)
      CALL EXECUT(DIMEN)
      STOP
      END

      SUBROUTINE EXECUT(DIMEN)
      COMMON VN(3,3,70),PRODUC,CAPAC,POPUL
      INTEGER DIMEN
      DIMENSION STORG(70),STATE(3),GPD(70)
      REAL*8 STATE /'DRY','NORMAL','WET'/
      L=0
      DO 50 I=1,DIMEN
      STORG(I)=FLOAT(1000*(I-1))
50    CONTINUE
      DO 1 I=1,3
         DO 2 K=1,DIMEN
         VN(I,1,K)=AMIN1(STORG(K),PRODUC)
         VN(I,2,K)=UTILS(VN(I,1,K))
         VN(I,3,K)=VN(I,2,K)
2     CONTINUE
1     CONTINUE
7     KEY=0
      DO 3 I=1,3
         CALL NXTSTG(I,DIMEN)
3     CONTINUE
      L=L+1
      DO 4 I=1,3
         DO 5 K=1,DIMEN
           IF((VN(I,2,K)-VN(I,3,K)).GT.10.) KEY=1
           VN(I,3,K)=VN(I,2,K)
5     CONTINUE
4     CONTINUE
      IF(L.EQ.10) GO TO 20
      IF(KEY.EQ.1) GO TO 7
20    DO 9 INDEX=1,3
         DO 10 II=1,DIMEN
            GPD(II)=CONVER(VN(INDEX,1,II))
10    CONTINUE
      WRITE(6,100) STATE(INDEX)
100   FORMAT(////' RESULTS WHEN INITIAL CONDITIONS ARE ',A6)
         DO 8 M1=1,DIMEN,12
         M2=M1+11
         WRITE(6,101) (STORG(I),I=M1,M2),(VN(INDEX,1,J),J=M1,M2),(VN(
     1INDEX,2,K),K=M1,M2),(GPD(L),L=M1,M2)
101    FORMAT(//' WATER ON HAND:    ',12(1X,F7.0)/' OPTIMAL CONSUMP: ',1
     12(1X,F7.0)/' TOTAL UTILITY:    ',12(1X,F7.0)/
     2' GAL/PERSON/DAY: ',12(1X,F7.0)//)
8     CONTINUE
9     CONTINUE
      RETURN
      END
```

```
      SUBROUTINE NXTSTG(IWET,DIMEN)
      COMMON VN(3,3,70),PRODUC,CAPAC,POPUL
      INTEGER DIMEN
      DIMENSION RAINFL(36)
      DATA RAINFL /.002,3*.0005,4*.0006,.009,2*.011,.015,.016,.024,.035,
     1.047,.078,.102,.12,.06,.04,.035,.025,2*.02,5*.015,2*.012,.011,
     22*.01,.169/
      ALPHA=.9
      DO 1 I1=1,DIMEN
         DMAX=0.
         UMAX=-10000.
      STORG1=FLOAT(1000*(I1-1))
         PUMPGE=AMIN1(STORG1,PRODUC)
      MAXD=IFIX(PUMPGE/1000.+1.5)
         DO 2 I2=1,MAXD
           DECIS=FLOAT(1000*(I2-1))
           SUM=0.
             DO 3 I3=1,36
             RAIN=FLOAT(I3)
             RETURN=RUNOFF(RAIN,IWET)
             STORG2=AMIN1(STORG1+RETURN-DECIS,CAPAC)
             IWET2=2
            IF(RETURN.GT.148793.) IWET2=3
            IF(RETURN.LT.11601.) IWET2=1
            INDEX=IFIX(STORG2/1000.+1.5)
            SUM=SUM+RAINFL(I3)*VN(IWET2,3,INDEX)
3     CONTINUE
         UEXP= UTILS(DECIS)+ALPHA*SUM
        IF(UEXP.LT.UMAX) GO TO 2
        UMAX=UEXP
        DMAX=DECIS
2     CONTINUE
      VN(IWET,1,I1)=DMAX
      VN(IWET,2,I1)=UMAX
1     CONTINUE
      RETURN
      END
```

```
      FUNCTION RUNOFF(RAIN,IWET)
      RUNOFF=5296.38932*RAIN+8433.159*FLOAT(IWET)-71058.62
      RUNOFF=AMAX1(RUNOFF,0.)
      RETURN
      END

      FUNCTION UTILS(WATER)
      GPD=CONVER(WATER)
      IF(GPD.LT.65.) UTILS=1.617*GPD-80.105
      IF(GPD.GE.65..AND.GPD.LE.175.) UTILS=(79.154)*SQRT(GPD)-(37.129)*
     1ALOG(GPD)-2.72*GPD-281.354
      IF(GPD.GT.175) UTILS=(.05957)*GPD+87.83
      RETURN
      END

      FUNCTION CONVER(X)
      COMMON VN(3,3,70),PRODUC,CAPAC,POPUL
      CONVER=(731.27)*(X-640.)/POPUL
      CONVER=AMAX1(CONVER,0.)
      RETURN
      END
```

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